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# Observation of rogue waves in a 980nm-laser diode subject to filtered optical feedback

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## Abstract

**In this work, rogue waves are observed in a 980 nm laser diode subject to filtered optical feedback via an fibre Bragg grating. A rogue-wave map is established for the first time experimentally as functions of optical feedback ratio and laser current. Rogue waves in our laser system are identified as a part of low frequency fluctuation jump-ups.**

## I. INTRODUCTION

The rogue waves phenomena have been observed for centuries. In ocean science, they are defined as waves greater than their mean value plus four to eight times the standard deviations [1]. Such huge waves are categorised as extreme events. These extreme events are rare and result from non-linear systems. These events have attracted attention over the decade in order to study rogue waves in ocean science [1], extreme climate [2], financial crisis [3], etc.

The first experimental observation in a non-linear optical system was reported by Solli et al. [4]. Since then, optical rogue waves have been studied in mode-locked lasers [5], in laser diodes with optical injection [6], in a laser diode subject to optical phase-conjugate feedback [7] and in a laser diode with a very short cavity [8].

We report for the first time the observation of rogue waves in a high power laser diode emitting at 980 nm subject to a filtered optical feedback via a Fibre Bragg Grating (FBG). The main application of these systems deals with Erbium-Doped Fibre Amplifier (EDFA) that are widely used in optical communications networks, where they are used as pump modules. The objective of the current study is to determine the parameter range where such non-linear phenomena appear.

Laser diodes can be rendered chaotic when subject to optical feedback. This is quite well-known and has been studied for decades [9]. According to optical feedback ratio, laser diodes show different dynamical behaviours. Low-Frequency Fluctuation (LFF) is one of the behaviours in the coherence collapse regime with intensity drop-out and jump-up. Although drop-out behaviour is intensively investigated, jump-up behaviour is studied very little [10].

In our work, we will establish a rogue wave map as a function of two parameters: the laser drive current and the

optical feedback ratio. We will also show how LFF behaviour is related to the appearance of rogue waves.

## II. EXPERIMENTAL SETUP

The experimental setup is shown schematically in Fig. 1. The emission of the Laser Diode (LD) at 980 nm is coupled to a Variable Optical Attenuator (VOA) and an FBG. The reflected emission from the FBG is fed back to the LD through VOA1, forming an external cavity of 4.2 m. The reflectivity of the FBG is 30 % at 980 nm with a linewidth of 0.6 nm and the total attenuation is controlled by the automated VOA 1. Its output is transmitted to two Photo-Detectors (PD1 and PD2) through an optical isolator, VOA 2 and a 50:50-optical coupler. The PD signals are recorded by a radio frequency (RF) spectrum analyser and a digital oscilloscope. In order to investigate rogue waves, electrical signals beyond 100 MHz bandwidth are filtered out. The oscilloscope records time traces with 200 000 data points in a time window of 40  $\mu$ s.

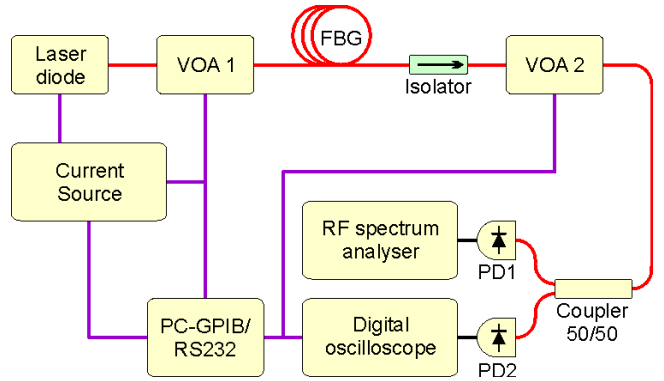


Fig. 1. Experimental setup.

The laser power is as high as 350 mW at a current of 500 mA and a temperature of 25 °C. The threshold current of the solitary laser diode is 70 mA. Taking into account the round trip attenuation of VOA 1, and the 30 % reflectivity of FBG, the feedback ratio ranges from 0 % to 12.5 %.

## III. EXPERIMENTAL RESULTS

Figure 2 shows rogue waves obtained from the system for different currents and feedback ratios. In our work, the definition of rogue waves is the wave mean value plus 8 times of the standard deviation as in ocean science. The

red lines in the figures represent the limit of rogue waves based on this definition. In Fig. 2(a), a 10ns-pulse width single rogue wave is observed for a 5.5%-feedback ratio and a 240mA-current. As seen in the figure, the rogue wave clearly exceeds 8 times the deviation. It has been verified that the dynamical behaviour of the rest of the time series is chaotic. At 241 mA and 5.5%, rogue waves appear more frequently (Fig. 2.b). At 0.5% and 167 mA, rogue waves occur even more frequently (Fig. 2.c). Thus, this cannot be considered as rare events.

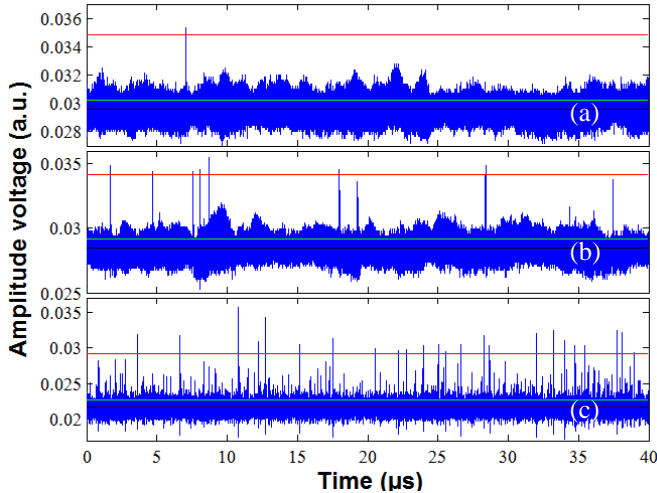


Fig. 2. Rogue waves generated at (a) 5.5% and 240 mA, (b) 5.5% and 241 mA and (c) 0.5% and 167 mA. The red, black and green lines represent the rogue waves threshold, the mean value and the standard deviation, respectively.

In order to study in more details, the number of rogue waves is counted for each 40 $\mu$ s-time trace as a function of both the feedback ratio and the laser current. These numbers are used for establishing the map shown in Fig. 3. To establish the map, the laser current is swept from 50 mA to 500 mA which is 7 times the threshold current of the solitary laser and the feedback ratio is varied from 0.5 % to 12.5 % by 0.5 %. The number of rogue waves is coded as shown in the colour code scale. Figure 3 exhibits 2 zones of appearance of the rogue waves. The first zone (0.5 % to 2 % and 100 mA < I < 400 mA) exhibits more frequent appearance of rogue waves than the second one (4 % to 6 % above 150 mA). However it is clearly seen that rogue waves disappear as increasing further the laser current. Apart from these zones, the system is free from rogue waves. Note more specifically that for 2.5 % and 3 % and for I > 200 mA the system is optimum.

As mentioned above, our laser system is a chaotic system. Therefore, it also exhibits LFF such as drop-out and jump-up. Our previous work showed the drop-out and jump-up zones in a chaotic behaviour map [11]. From this work, the zones of these behaviours are indicated in Fig. 3 where it clearly appears that rogue waves are part of jump-ups which can occur rarely with intense pulses. At high currents, rogue waves occur so frequently that the mean value and the standard deviation drift away up. Thus by the oceanographic definition, rogue waves disappear as increasing further the laser

current. However, extreme pulses still exist. Moreover, note that rogue waves exist up to 6 % of feedback ratio which is also approximately the limit of existence of the LFF drop-outs.

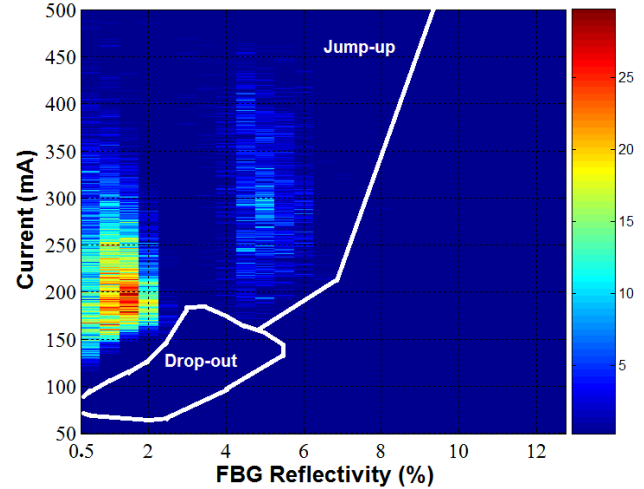


Fig. 3. Map of rogue waves as a function of the FBG reflectivity (optical feedback ratio) and the laser current. The drop-out and jump-up zones are indicated.

#### IV. CONCLUSIONS

For the first time, we have observed rogue waves in a high-power laser diode emitting at 980 nm subject to filtered optical feedback via an FBG. A map has been established experimentally as a function the two parameters (feedback ratio and current). According to the map, optical rogue waves exist in very specific and limited ranges of parameters. Apart from these zones, the system is free from rogue waves.

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